Title: **Advanced Modeling and Active Control Techniques for Aircraft Load Alleviation**

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Dr. Nicolas Fezans[3], Dr. David Quero[4]

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Abstract:

In order to allow for a more economic and environmentally friendly aircraft operation and to fulfill the greener imperative demanded by today's society, fuel savings and cost reduction play a key role in the development of modern aircraft. Besides the efficiency of engines and aerodynamics, the aircraft weight has a major impact on fuel consumption. Reducing structural wing loads caused by atmospheric disturbances (such as gusts, turbulence and wake vortices) thereby became a main research interest of today's aircraft industry. Reducing such loads will allow the aircraft manufacturer building and certifying aircraft to smaller load envelopes, inherently reducing the airframe structural weight and thus reduce fuel, emissions and cost. In this contribution we discuss latest research and development trends in the field of modelling and control for load alleviation on modern, fly-by-wire aircraft. Covering a broad range of relevant topics, the paper is divided into four main subtopics as follows:

(i) For analyzing loads on the aircraft in an early design stage with high fidelity simulation techniques, detailed models of the structure and the aerodynamics are generated. Here, we discuss the latest developments on how these complex aeroelastic models (generated by CFD methods, e.g.) are derived and can be approximated by lower order models for facilitating the subsequent controller design.

(ii) Directly linked to the modelling in (i) is the feedback control design task. The use of available local measurements as well as virtual sensors for incoming gusts provides a profound basis for alleviating the associated structural loads. This subsection discusses the current trends in control development such as estimator design and robust control techniques to feed back the gust estimates.

(iii) Also, in direct link to the modelling (i) but also to the lidar sensors (iv) feedforward control allows for an enhanced load alleviation performance than a pure feedback due to its anticipative behavior (control actions can be taken earlier). In contrast to the feedback approaches (ii), it requires additional forward sensing capabilities, such as lidar for the gust anticipation. Detailed models of these sensors are needed to allow for a dedicated feedforward control design: these lidar sensor models are investigated in great depth within a dedicated activity (iv) and in surrogate models – derived from them – are considered in the feedforward design tool. In this subtopic the surrogate models of the lidar sensors, the wind reconstruction algorithms as well as the feedforward load alleviation design workflow are presented.

(iv) The feedforward control approaches in (iii) require measurements of the incoming gust, which shall be provided by advanced lidar measurement systems. The latest development directions for adapting the lidar technology to fulfil the needs of feedforward gust load alleviation applications are discussed in this subtopic. These progresses represent a key enabling technology for viable anticipation of incoming gusts and winds, paving the way for improving the gust load alleviation capabilities for future aircraft generations.

The presented work is performed in the context of the project *New Innovative Aircraft Configurations and Related Issues*. This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No CS2-AIR-GAM-2014-2015-01.

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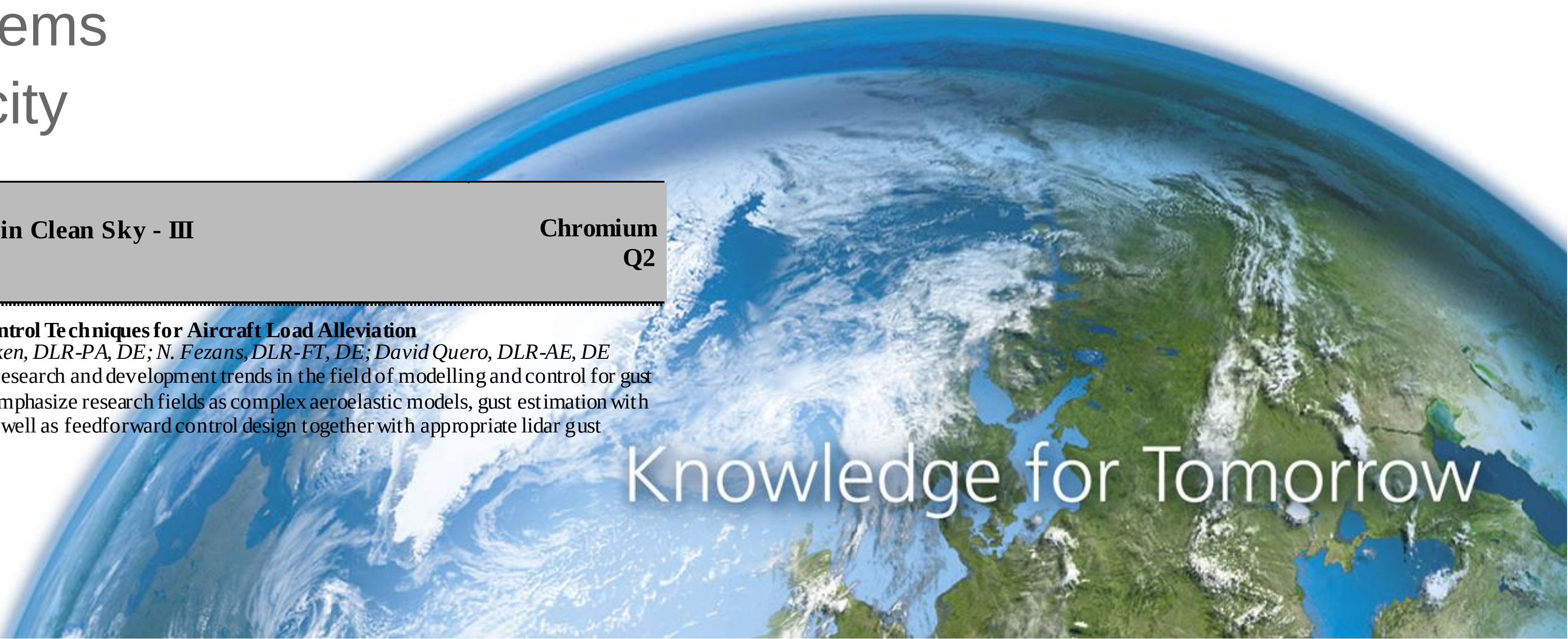
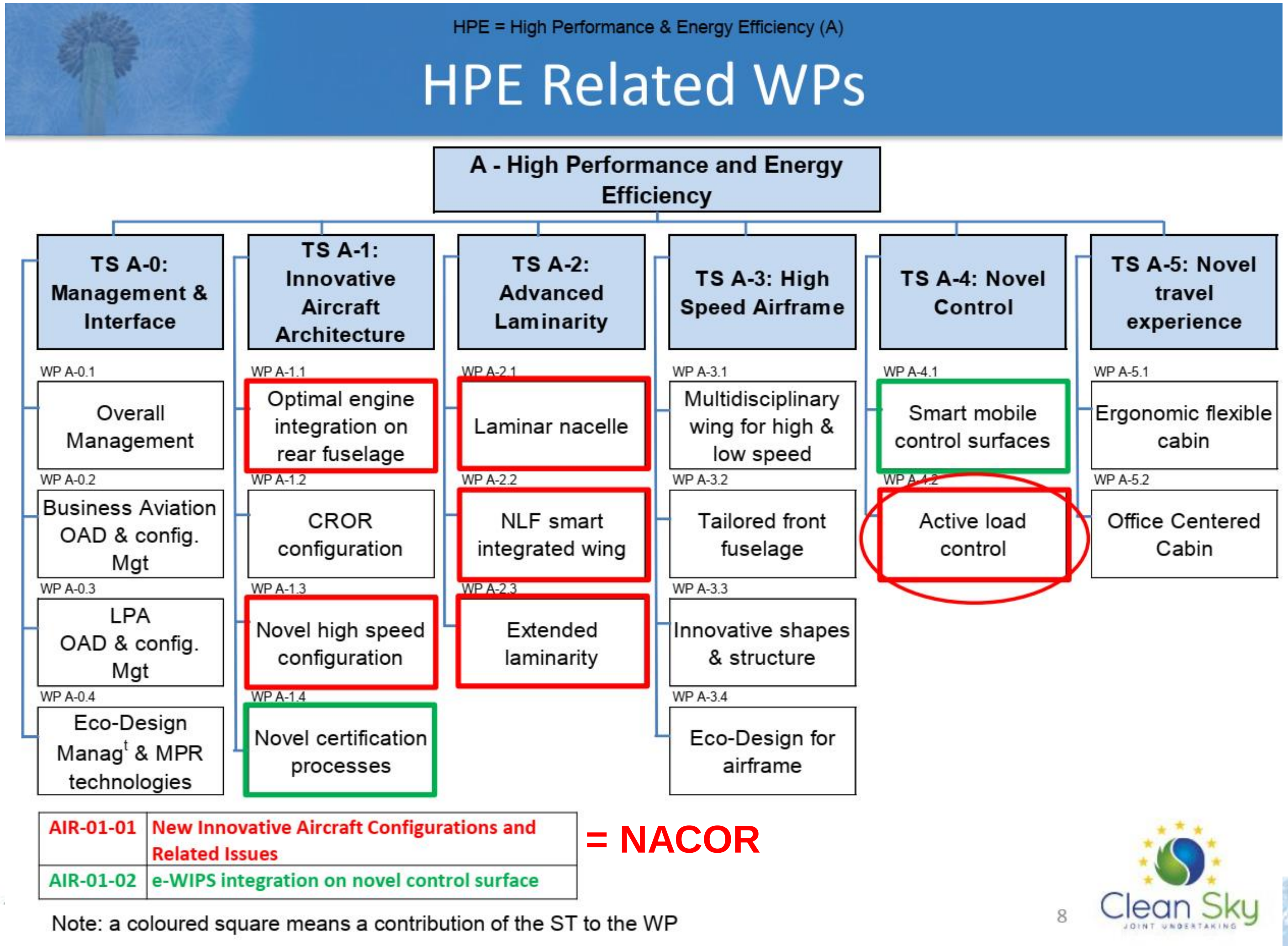
6.D Di, 01.10.	**Aviation & Environment: DLR achievements in Clean Sky - III** Sitzungsleitung: T.Haase, DLR, DE			**Chromium Q2**
16:50	17:15	0084	**Advanced Modeling and Active Control Techniques for Aircraft Load Alleviation** *D. Ossmann, DLR-SR, DE; P. Vrancken, DLR-PA, DE; N. Fezans, DLR-FT, DE; David Quero, DLR-AE, DE* In this contribution we discuss latest research and development trends in the field of modelling and control for gust and turbulence load alleviation. We emphasize research fields as complex aeroelastic models, gust estimation with robust feedback control techniques as well as feedforward control design together with appropriate lidar gust sensory.	



DLR

Advanced Modeling and Active Control Techniques for Aircraft Load Alleviation

- Group work in the framework of CleanSky Smart Fixed Wing Aircraft and CleanSky 2 – Airframe/NACOR



- ITD (Integrated Technology Demonstrator)
  - …
  - Airframe
    - Activity Line „High Performance & Energy Efficiency“ (A)
      - Technology Stream „Novel Control“
        - *Work Package Active Load Control (WP A-4.2)*

Advanced Modeling and Active Control Techniques for Aircraft Load Alleviation

- Group work in the framework of CleanSky Smart Fixed Wing Aircraft and CleanSky 2 – Airframe/NACOR
- In collaboration with ONERA, Dassault Aviation and AIRBUS
- Overview on all tasks:

Modeling | Control design

- Aeroservoelasticity
- Integrated model
- LIDAR sensors

Control design | Methodologies

- Nonlinear multi-objective
- Robust control / gust est.
- Time-freq. separated
- Preview control

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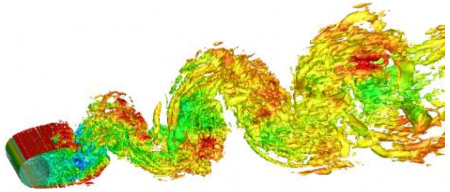
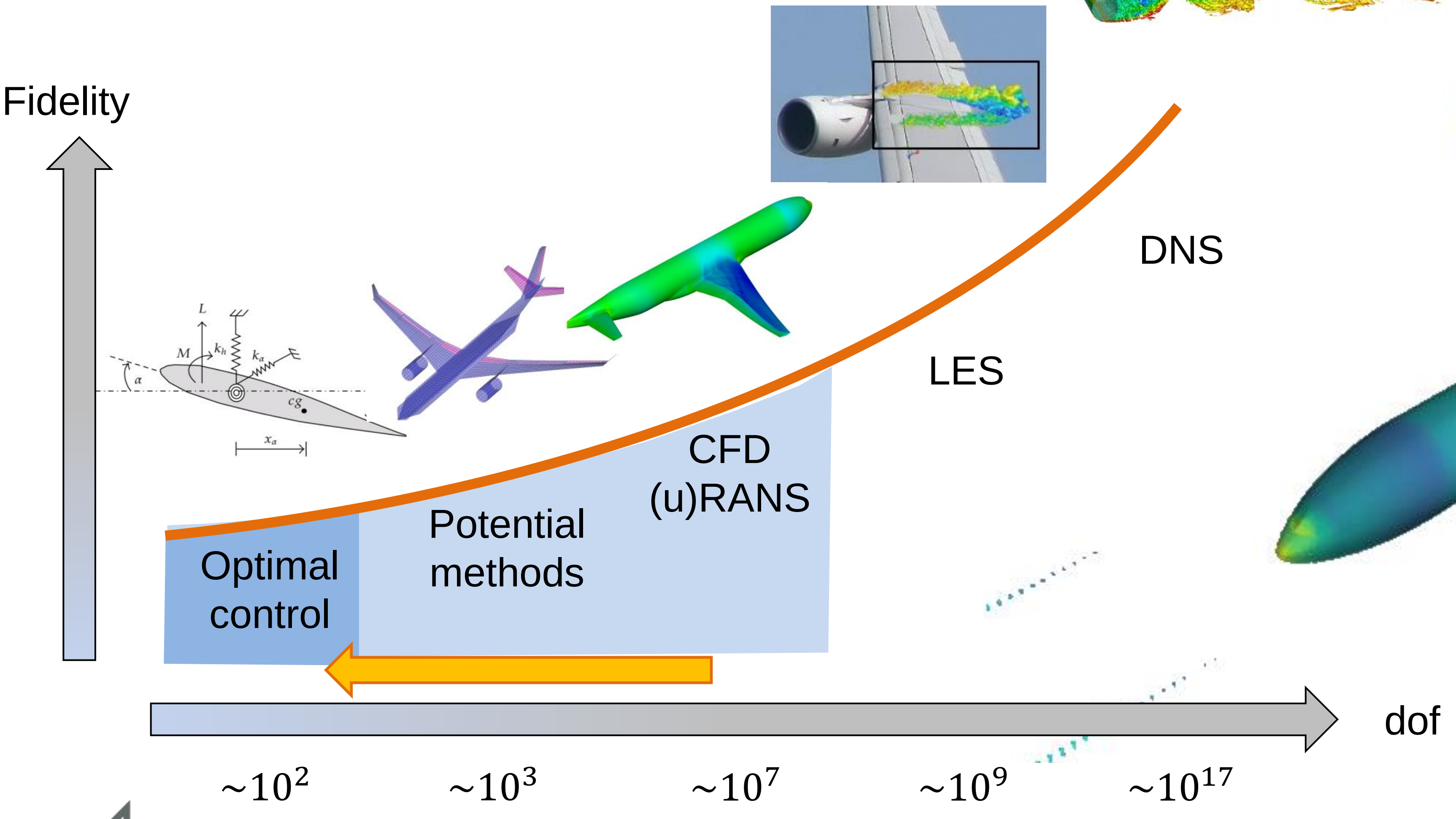
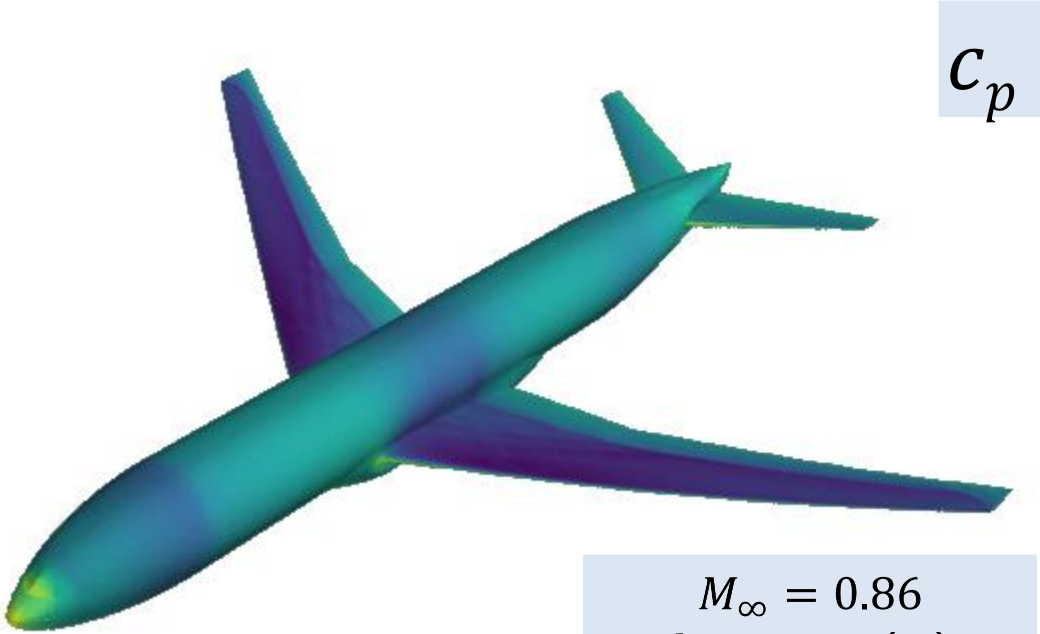
Modeling – High Fidelity Aeroservoelasticity

- Hierarchy of aerodynamic models





- Example: URANS → $\sim 22 \cdot 10^6$ dof



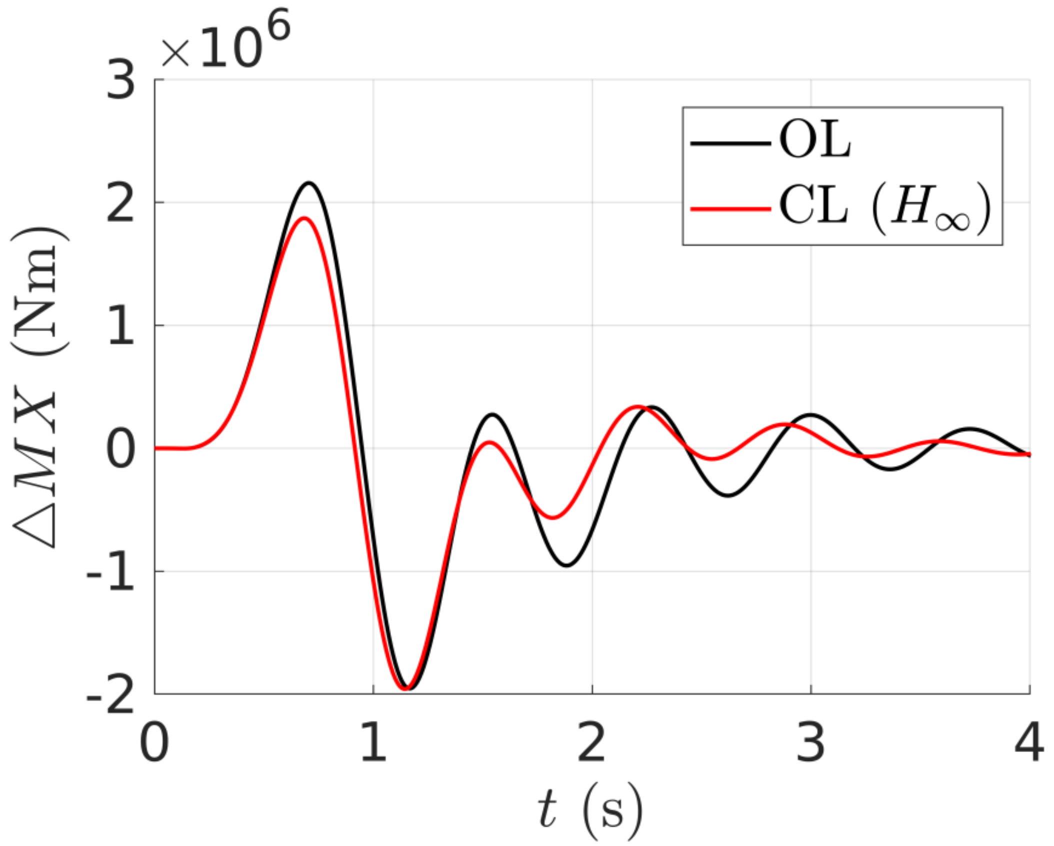
$$M_\infty = 0.86$$
$$h = 9100 \text{ (m)}$$
$$\alpha_0 = 1.641 \text{ (deg)}$$
$$H = 350 \text{ (ft)}$$
$$\alpha_{eq} = 1 \text{ (deg)}$$

Modeling – High Fidelity Aeroservoelasticity (II) – Load Alleviation Design

Application of optimal control techniques with high-fidelity aeroservoelastic models:

- Loewner-Framework:
  - Automatic generation of the generalized state-space aeroservoelastic model in the time-domain (without parameter tuning as in the classical rational fitting approaches)
    reducing the aeroservoelastic model with 22 million dof to 160 dof
  - Nonlinear optimization structured H_∞ controller (non-convex + non-smooth), local optimality but used in practice
  - Optimal feedback control for gust load alleviation (aileron symmetric deflection)

- Wing root bending (incremental) with H_∞-(sub)optimal structured controller (153+7 states)



[Poussot-Vassal/Quero/Vuillemin IFAC 2018]

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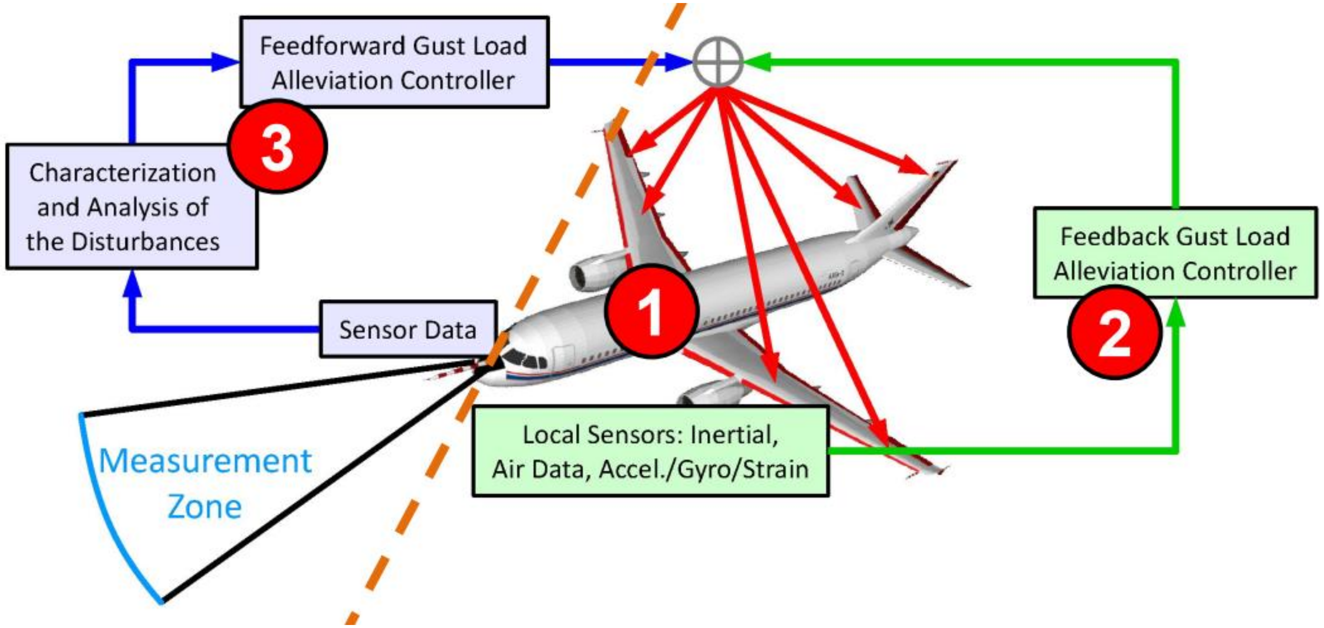
Modeling – Doppler LIDAR for Gust Load Alleviation

Feed-Forward Control chain:

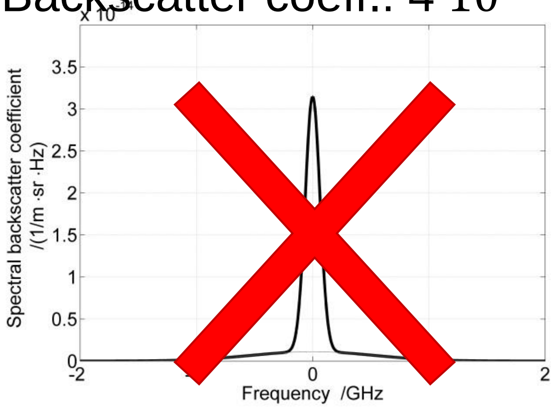
- Sensor – Gust retrieval – Controller – A/C+flow

Preliminary remarks:

- Disturbance (gust) anticipation →Feedforward GLA
  → Direct-Detection Doppler Wind LIDAR (DWL)
- Retreiving Doppler shifted laser frequency (line-of-sight wind speed)
  from temperature-broadened spectrum
- DWL ≙ Spectral Analyzer

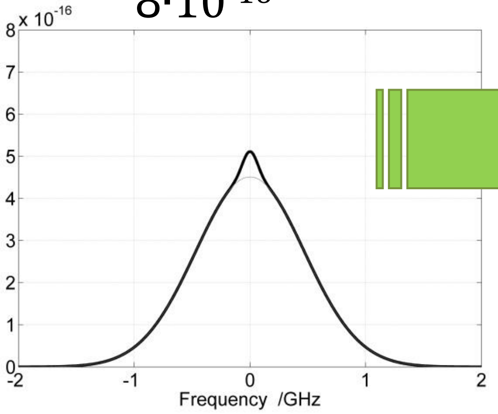


Backscatter coeff.: $4 \cdot 10^{-14}$

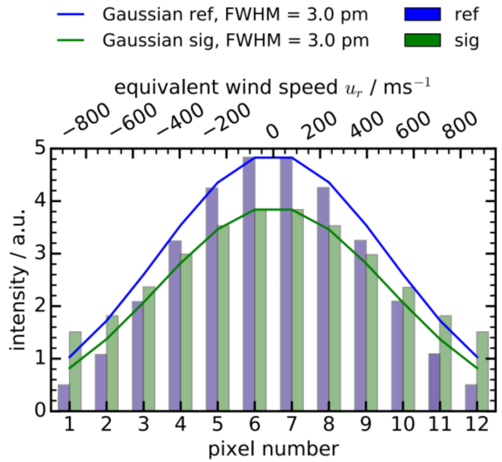


Plan. boundary layer

$8 \cdot 10^{-16}$



Cruise altitude



Modeling – Doppler LIDAR for Gust Load Alleviation – Measurement dispersion

Feedforward controller design:

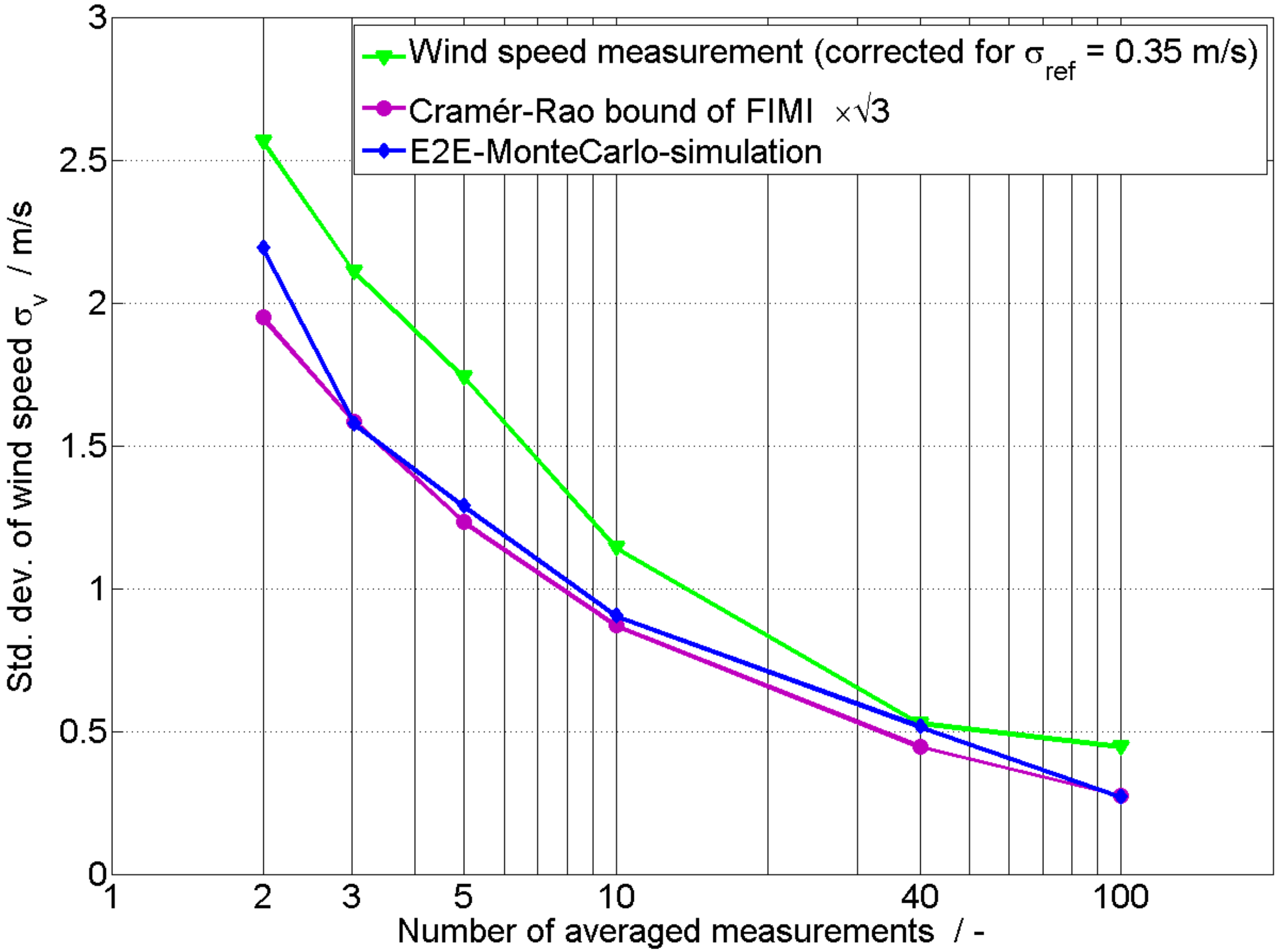
- Sensor error modelling

- Here: triple approach:
  - LIDAR sensor End-to-End simulator (MonteCarlo, noise processes)
  - Analytical estimator: Cramér-Rao-bound of (non-)ideal spectral analyzer
  - LIDAR prototype with field tests

→ Analysis of wind speed measurement dispersion

Cramér-Rao-Bound as “surrogate” model (instead of E2E-MC-Simulations)

[Herbst/Vrancken 2016, 2018, 2019]



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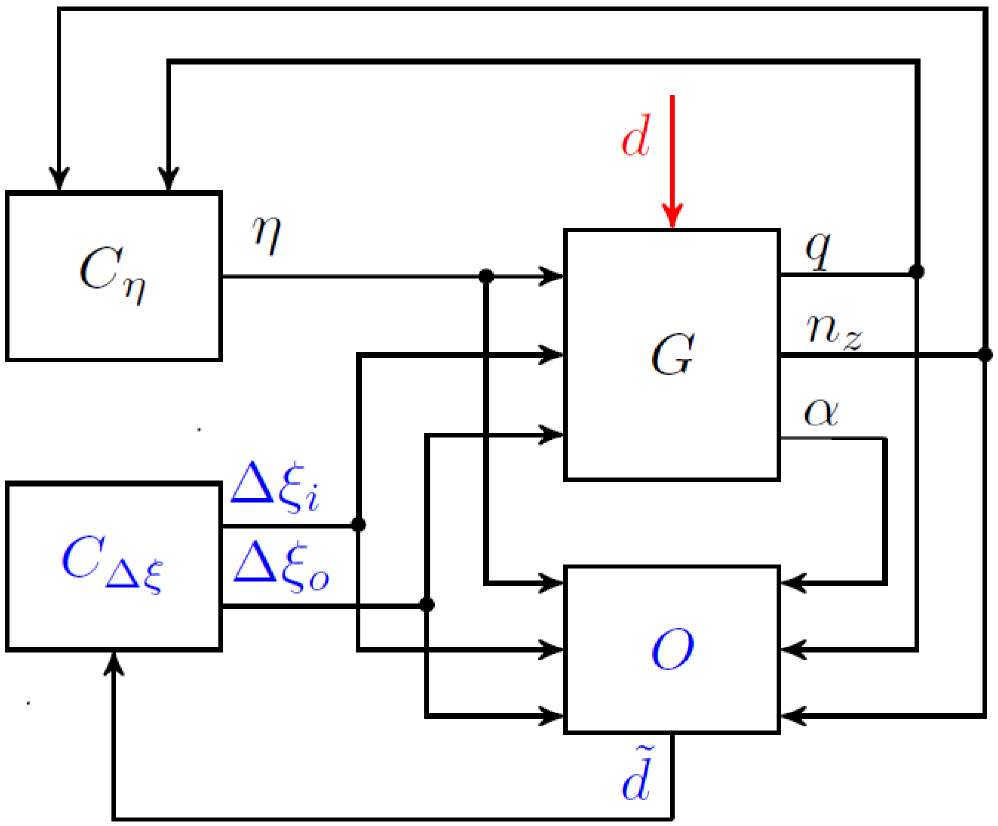
Control Design Methodologies – Estimator-Based Load Reduction (1/2)

- Provide information on the gust to the load alleviation controller using only standard sensors (e.g. no LIDAR)
  ➔ Estimator to estimate unknown disturbance
- Prevent the load alleviation controller from acting when no or low disturbance (gust/turbulence) is present
  ➔ "Feedforward-like" controller interpretation
- Explicit gust estimator eases the design of the load controller



Streamlined design procedure:

1. Model approximation using advanced reduction techniques
2. Minimal estimator design using nullspace-based approach and optimization
3. Simple linear controller development based on robust control techniques
4. Validation using full order simulation model with actuators sensors and time delays

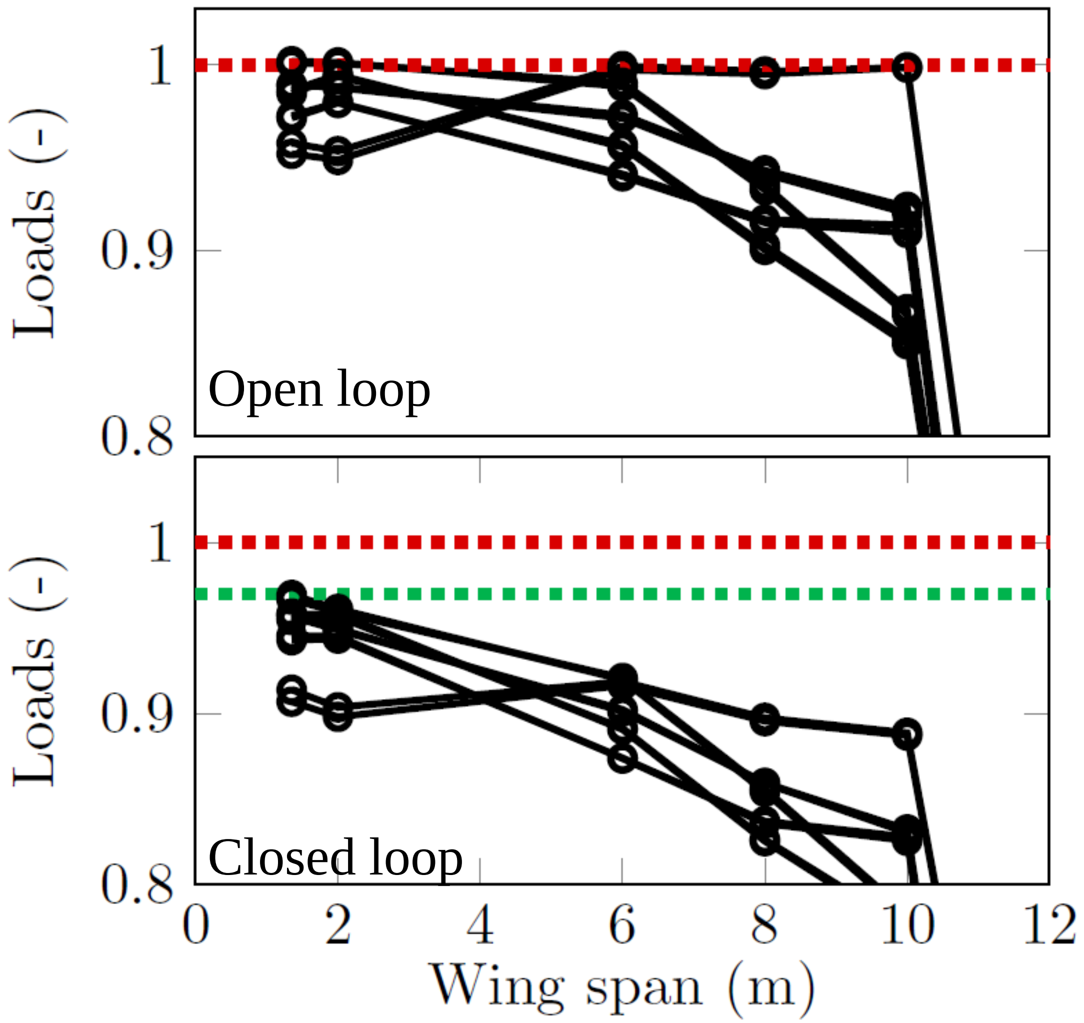
Control Design Methodologies – Estimator-Based Load Reduction (2/2)

Simulation-based analysis on the 10 available mass/flight points for the "Generic Business Jet Aircraft" provided by Dassault Aviation.

Simulation model includes nonlinear actuators, sensors and time delays.

Results

- Reduction of worst case loads over all gust profiles
- 3% at the wing root and up to 10% on the outer wing
- Handling qualities stay the same (by design!)



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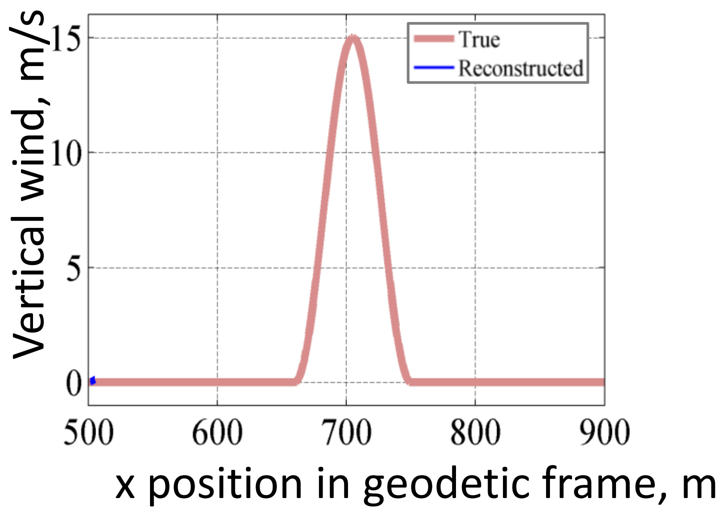
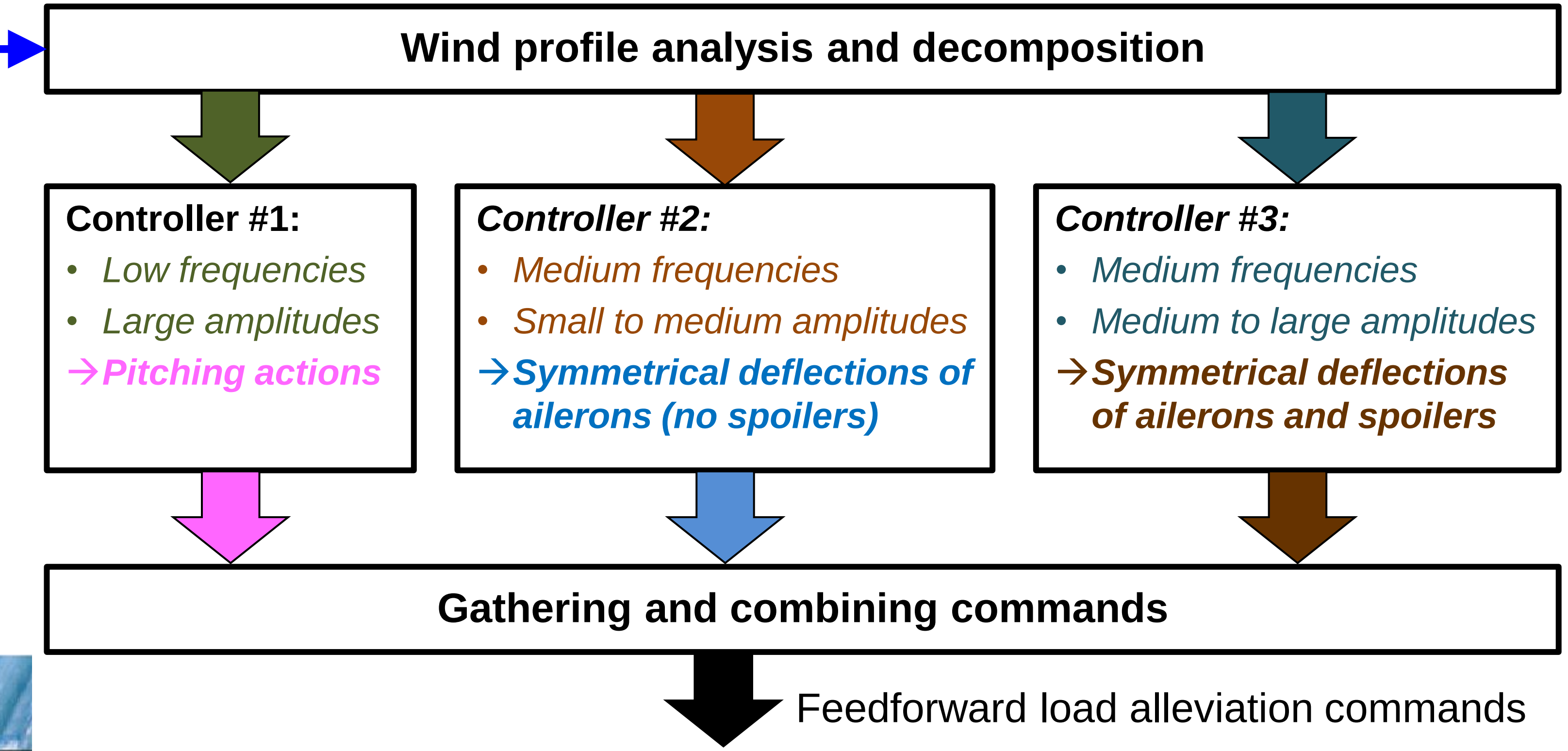
Control Design Methodologies – Time-Frequency-Separated GLA Controllers

- For cases where a portion of a disturbance signal is known in advance
- Useful for satisfying some strongly nonlinear allocation constraints (e.g. spoilers only for large gusts)
- Design and tailored for a particular XRF-1-based use case
  ➔ easy tuning of strongly nonlinear distributed load control function
  ➔ each controller is simple and can also be tuned with the advanced tools from the linear control theory

Reconstructed wind profile ahead of the aircraft





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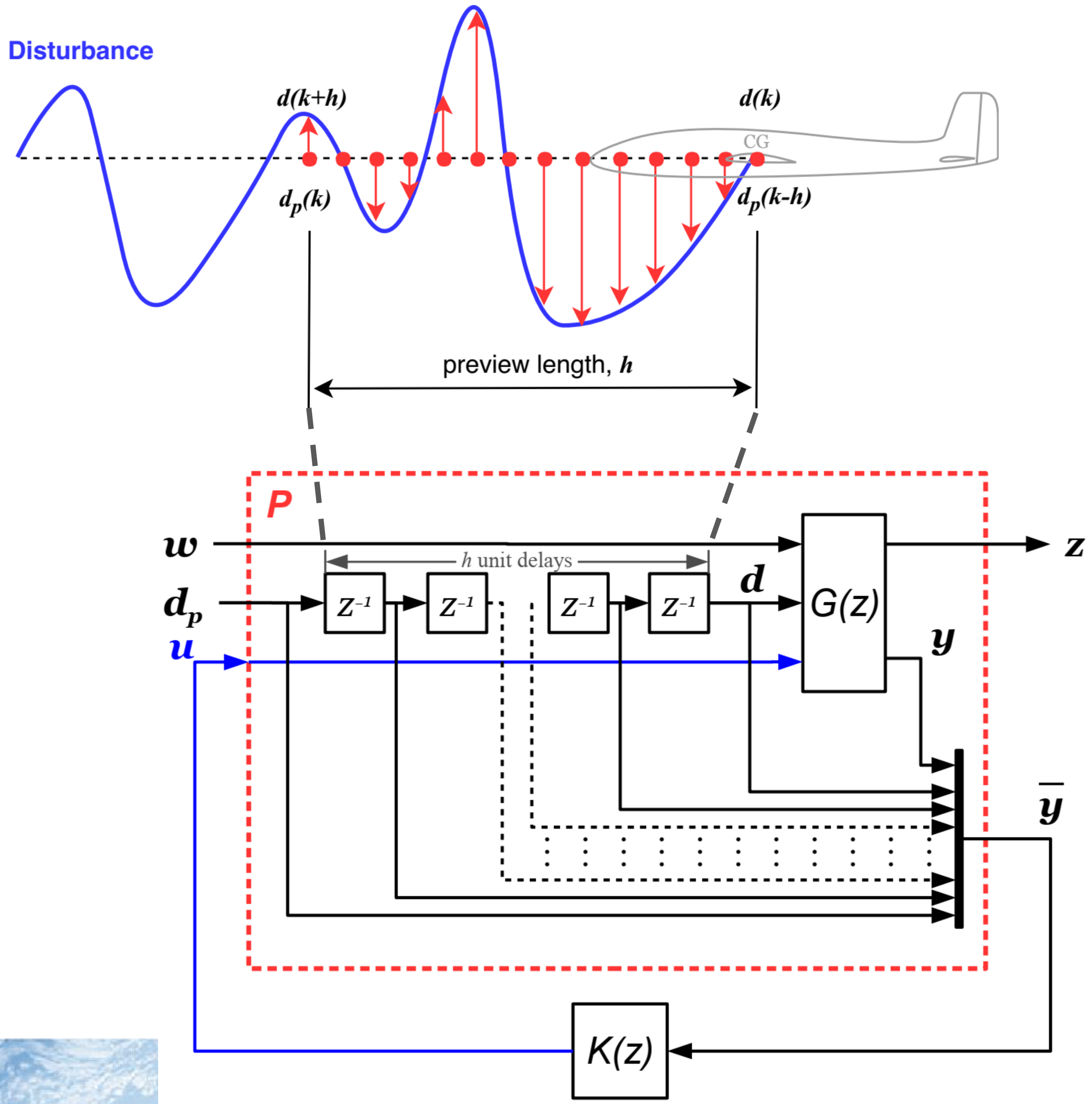
Control Design Methodologies – Preview Control

- Alternative to the time-frequency-separated control structure for cases with no allocation constraints (remark: both could be combined though)

- Provide a closed form control design permitting to combine the nice properties of structured H_∞ control while taking advantage of the "previewed" information on the forthcoming gusts/turbulence

- Step towards automatic tuning of this kind of GLA functions
  ➔ Also helpful for defining LIDAR sensor requirements

- On-going work (will soon be applied to the Generic Business Jet Aircraft within CS2-AIR-NACOR)



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- Only a brief glance on DLR contributions – further info in publication list in next slides

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Acknowledgement

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  - CleanSky Smart Fixed Wing Aircraft Integrated Technology Demonstrator (SFWA-ITD) (contract # CSJU-GAM-SFWA-2008-01) being part of the 7th Framework Programme research and Innovation framework program of the European Commission.
  - Clean Sky 2, AIRFRAME Integrated Technology Demonstrator platform ”AIRFRAME ITD” (contract # CSJU-CS2-GAM-AIR-2014-15-01 Annex 1, Issue B04, 2015) being part of the Horizon 2020 research and Innovation framework program of the European Commission.

- Thank you to the partners directly involved: ONERA, Dassault Aviation, AIRBUS!

Selected Publications

- Fezans, N.; Joos, H.-D., Deiler, C.; *Gust load alleviation for a long-range aircraft with and without anticipation*, CEAS Aeronautical Journal, 2019, DOI: 10.1007/s13272-019-00362-9.
- Fezans, N.; Schwithal, J., Fischenberg, D.; *In-flight remote sensing and identification of gusts, turbulence, and wake vortices using a Doppler LIDAR*, CEAS Aeronautical Journal, Vol. 8, No.2, 2017, DOI: 10.1007/s13272-017-0240-9.
- Herbst, J., Vrancken, P.: *Design of a monolithic Michelson interferometer for fringe imaging in a near-field, UV, direct-detection Doppler wind lidar*. Appl. Opt. **55**(25), 6910–6929 (2016), DOI: 10.1364/AO.55.006910
- Herbst, J.,: *Development and test of a UV lidar receiver for the measurement of wind velocities aiming at the near-range characterization of wake vortices and gusts in clear air.* Doctoral dissertation, Ludwig Maximilians University Munich (2018).
- Herbst, J., Vrancken, P., Wirth, M.*; Development and test of a Fringe-Imaging Direct-Detection Doppler Wind Lidar for Aeronautics* . In: Proceedings of the 29th laser radar conference, Hefei, China (2019).
- Khalil, A., Fezans, N.: *A Multi-Channel H_∞ preview control approach to load alleviation function design*. In: 5th CEAS Conference on Guidance, Navigation & Control. Milano, Italy (2019).
- Khalil, A., Fezans, N.: *Performance enhancement of gust load alleviation systems for flexible aircraft using H_∞ optimal control with preview*. In: AIAA Scitech Forum. San Diego, CA, USA (2019), DOI: 10.2514/6.2019-0822.
- Ossmann, D., Poussot-Vassal, C.: *Minimal order disturbance estimator design for aircraft load alleviation control*. In: IEEE Conference on Control Technology and Applications (CCTA). IEEE, Copenhagen, Denmark (2018), DOI: 10.1109/CCTA.2018.8511549.
- Poussot-Vassal, C., Quero, D., Vuillemin, P.: *Data-driven approximation of a high fidelity gust-oriented flexible aircraft dynamical model*. IFAC-PapersOnLine **51**(2), 559–564 (2018), DOI: 10.1016/j.ifacol.2018.03.094.